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Fast Amplitude Estimation for Low-Voltage Ride-Through Operation of Single-Phase Systems

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ABSTRACT Estimating the amplitude of the grid voltage is important for low-voltage ride-through (LVRT) operation in single-phase systems. It requires fast dynamics and is typically achieved through a phase-locked loop (PLL). This paper proposes a fast amplitude estimation (FAE) method without a PLL structure. The grid voltage is formulated as a vector sum of sine and cosine functions, resulting in an algebraic model with two unknown parameters. The proposed FAE identifies the two parameters, and thus achieving a fast fault detection (i.e., the amplitude estimation). Experimental results verify the performance of the proposed method in terms of fast dynamics.

INDEX TERMS Amplitude estimation, voltage sags, low-voltage ride-through (LVRT), parameter identification, single-phase systems, grid synchronization.

I. INTRODUCTION

In recent years, renewable energy sources, e.g., wind and photovoltaic (PV) power, have become essential in the grid modernization. However, the intermittent and non-dispatchable nature of the renewable energy challenges the grid stability [1], [2]. To enhance the resilience and robustness of power systems, grid codes are released to guide the integration of renewable energy [3]–[5]. For instance, it is now mandatory for grid-connected units to ride through temporary low-voltage grid faults, known as the low-voltage ride-through (LVRT) operation. In the LVRT operation, the generation units may provide dynamic grid support by injecting reactive currents as many grid codes requirements [6]. Taking the Chinese grid code for PV as an example, the voltage profile and the corresponding reactive current requirement are shown in Fig. 1 [6]. It can be observed in Fig. 1(a) that in certain cases the generation units have to remain connected, even when the grid voltage drops to zero volts for a period up to 150 ms. The grid codes also define that the amount of the reactive current injected into the grids should change with the curve in Fig. 1(b) during LVRT. Meanwhile, the injection of the reactive current should be as fast as possible, since the required reactive power should be delivered into the grids through the PV generator within 30 ms. Thus, in order to ensure the stable operation of the grid-tied system, it is necessary to apply a fast fault detection method to the grid converter system. In details, the grid voltage amplitude should be estimated quickly so that the grid-tied inverter has sufficient time to response during fault periods [7].

There are many methods reported in the literature to estimate the grid voltage amplitude such as the root mean square (RMS) method [8], the peak voltage detection method [9] and the discrete Fourier transform (DFT) method [10]–[12]. However, the dynamics of above methods are slow. Both the RMS- and the DFT-based methods have at least one cycle time delay, and the solution based on the peak voltage detection results in at least one half cycle time delay. Alternatively, PLL-based methods, e.g., using the dq-transformation [13], the delayed signal cancellation-PLL (DSC-PLL) [14], [15] and the active power filter-PLL (APF-PLL) methods [16] can provide an estimate of the grid voltage amplitude. However, when the grid voltage suffers from the harmonic distortion, its detection performance will

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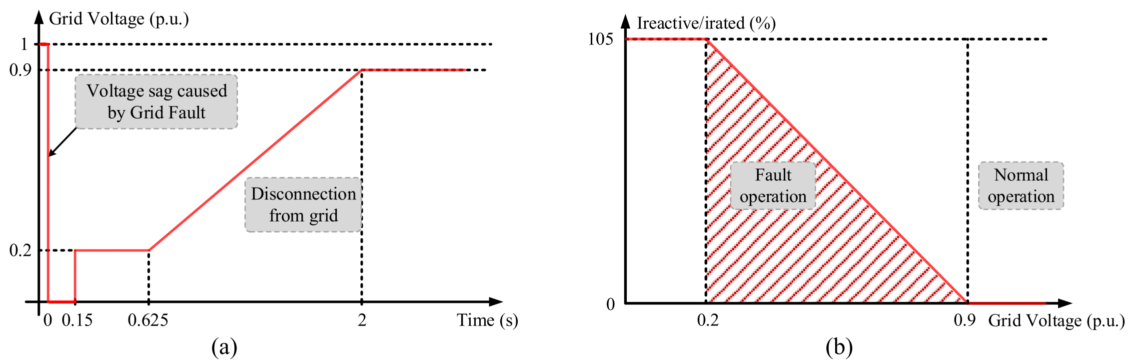

FIGURE 1. Low-voltage ride-through requirements in the Chinese grid code: (a) voltage profiles and (b) reactive current injection during the operation [4].

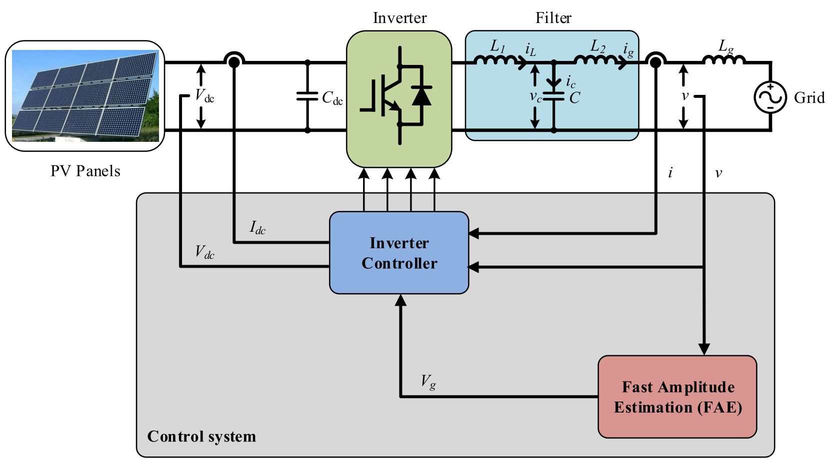

FIGURE 2. Control scheme of LVRT operation.

be degraded. To tackle this issue, the second-order generalized integration (SOGI-PLL) method [17]–[20] has been proposed. It is one of the most popular method among voltage detection because of its simple structure and good harmonic immunity. The enhanced PLL (EPLL) is another popular method in single-phase applications. The standard EPLL can track phase and frequency jumps without steady-state error. However, there will be a steady–state error in the presence of the frequency drifts [21]. In [22], an improved EPLL by adding multiple delayed signal cancellation filters has been proposed to tackle this problem. However, this EPLL have slow dynamics due to the filters. Meanwhile, there are several methods embed a digital filter into the PLLs to eliminate the harmonic components [23]–[26], such as the moving average filter based-PLL (MAF-PLL) method and the cascaded delayed signal cancellation based-PLL (CDSC-PLL) method. All the methods mentioned above has a good suppression effect on harmonics. Nevertheless, slow dynamics are associated with the PLLs, the settling time of these PLL-based methods usually lasts for one grid cycle, and hence, the entire LVRT performance is degraded.

In addition, in order to get the fast estimation of grid voltage amplitude during LVRT, there are some amplitude estimation methods with pre-filtering stage to deal with the harmonics and independent of PLL. For example, the method in [3] achieves the accurate detection under harmonic conditions and its response time depends on the voltage variation point. On the basis of the delay signal cancellation (DSC) [27], [28] module, the cascaded DSC (CDSC) module [29] is designed as another non-PLL technique for voltage amplitude estimation, which benefits from the fast dynamic response and the strong harmonic suppression ability. Another DSC operator is used to reduce the response time. In addition, [30] proposed an adaptive observer to estimate the voltage amplitude with fast dynamics. However, the main shortcoming of the non-PLL methods is that the performance will be degraded seriously when the grid voltage suffers from the frequency variation.

In this paper, a fast amplitude estimation (FAE) method is proposed for single-phase systems to enhance the LVRT operation. The proposed FAE takes the grid voltage as a vector sum of standard sine and cosine functions. Subsequently, an algebraic model is established based on the measured grid voltage, the sine and cosine functions, and two unknown parameters related to the grid voltage amplitude and the phase angle. Furthermore, a parameter identification method is introduced to identify the unknown parameters of the established model, resulting in the estimation of the voltage amplitude. It is worth to mention that the proposed FAE does not rely on PLLs and achieves fast dynamics. Experimental results also confirm the fast dynamics of the proposed method in Section IV.

II. THE CONTROL SYSTEM OF LVRT OPERATION

In Fig. 2, it shows the control scheme of LVRT operation to illustrate the function of the proposed FAE method in LVRT. The main structure consists of an inverter and its controller. According to the filtered voltage signal from the AC side of the inverter, the FAE method calculates the voltage amplitude and provides real-time information to the inverter controller. Meanwhile, the inverter controller asks the inverter to deliver the reactive power to the grids according to the amplitude information given by the FAE.

III. PROPOSED AMPLITUDE ESTIMATION METHOD

In single-phase systems, the grid voltage can be given by

$$v(t) = V_g \sin(\omega t + \phi) = V_g \sin\varphi \tag{1}$$

where $v(t)$ is the grid voltage, V_g, ω, ϕ and φ are the amplitude, frequency, initial phase angle and phase angle of the grid voltage respectively. Expanding (1) yields

$$\begin{aligned} v(t) &= V_g \cos\phi \sin\omega t + V_g \sin\phi \cos\omega t \\ &= a \sin\omega t + b \cos\omega t \end{aligned} \tag{2}$$

in which a and b are two unknown parameters as

$$a = V_g \cos\phi \tag{3}$$
$$b = V_g \sin\phi \tag{4}$$

Clearly, when a and b are known, the relationship between a and b indicates that the voltage amplitude can be obtained as

$$V_g = \sqrt{a^2 + b^2} \tag{5}$$

However, the parameters a and b in (2) are unknown. In the following, a and b are estimated, and the grid voltage amplitude is then calculated by (5).

For the grid voltage shown in (1), the estimated voltage can be expressed as

$$\hat{v}(t) = \hat{a}(t) \sin\omega t + \hat{b}(t) \cos\omega t \tag{6}$$

Accordingly, the error between the measured grid voltage and the estimation can be defined as

$$\varepsilon(t) = \hat{a}(t) \sin\omega t + \hat{b}(t) \cos\omega t - v(t) \tag{7}$$

$\varepsilon(t)$ represents the error between the estimation value and the actual value. $\hat{a}$ and $\hat{b}$ being the estimated values of a and b, respectively. With (7), the parameter estimators of a and b are proposed as

$$\dot{\hat{a}}(t) = -\gamma\varepsilon(t) \sin\omega t \tag{8}$$
$$\dot{\hat{b}}(t) = -\gamma\varepsilon(t) \cos\omega t \tag{9}$$

in which γ is the designed parameter of the proposed estimators and $\gamma > 0$. In the following, a mathematical analysis is presented to demonstrate that the proposed estimators in (7)-(9) can achieve zero steady-state error estimation of the unknown parameters, a and b.

For simplicity, the estimation errors are further defined as

$$\tilde{a}(t) = \hat{a}(t) - a \tag{10}$$
$$\tilde{b}(t) = \hat{b}(t) - b \tag{11}$$

Substituting (2) into (7) and considering (10) and (11), we obtain

$$\begin{aligned} \varepsilon(t) &= \hat{a}(t) \sin\omega t + \hat{b}(t) \cos\omega t - a \sin\omega t - b \cos\omega t \\ &= \tilde{a}(t) \sin\omega t + \tilde{b}(t) \cos\omega t \end{aligned} \tag{12}$$

A Lyapunov function is then defined as

$$V(t) = \frac{\tilde{a}^2(t) + \tilde{b}^2(t)}{2} \tag{13}$$

Subsequently, taking the derivative of Lyapunov function (14) yields

$$\dot{V}(t) = \tilde{a}(t)\dot{\tilde{a}}(t) + \tilde{b}(t)\dot{\tilde{b}}(t) \tag{14}$$

From (10) and (11), we have

$$\dot{\tilde{a}}(t) = \dot{\hat{a}}(t) = -\gamma\varepsilon(t) \sin\omega t \tag{15}$$
$$\dot{\tilde{b}}(t) = \dot{\hat{b}}(t) = -\gamma\varepsilon(t) \cos\omega t \tag{16}$$

Then, substituting (15) and (16) into (14) and together with (12), it results in

$$\begin{aligned} \dot{V}(t) &= -\tilde{a}(t)\gamma\varepsilon(t) \sin\omega t + \tilde{b}(t)\gamma\varepsilon(t) \cos\omega t \\ &= -\gamma\left(\tilde{a}(t) \sin\omega t + \tilde{b}(t) \cos\omega t\right)\varepsilon(t) \\ &= -\gamma\varepsilon(t)^2 \end{aligned} \tag{17}$$

Since $\gamma > 0$, the following holds

$$\dot{V}(t) \leq 0 \tag{18}$$

Considering that $\sin\omega t$ and $\cos\omega t$ are persistently exciting and also according to the adaptive control theory [31], it can be concluded that

$$\lim_{t\to\infty} \hat{a} = a \tag{19}$$
$$\lim_{t\to\infty} \hat{b} = b \tag{20}$$

This means that the proposed method in (7)-(9) can estimate the unknown parameters a and b with zero steady-state error. In addition, the proposed controller ensures that the estimated quantities converge to zero exponentially, which has been proved in [31]. Accordingly, with the obtained a and b, the amplitude of the grid voltage is estimated as

$$\hat{V}_g = \sqrt{\hat{a}^2 + \hat{b}^2} \tag{21}$$

where $\hat{V}_g$ is the estimation of V_g.

In summary, the proposed FAE can estimate the grid voltage amplitude, following (7)-(9) and (21). To give a more clear explanation of the proposed FAE, the control structure of the FAE method (7)-(9) and (21) is shown in Fig. 3. Moreover, the selection of the parameter γ is important for

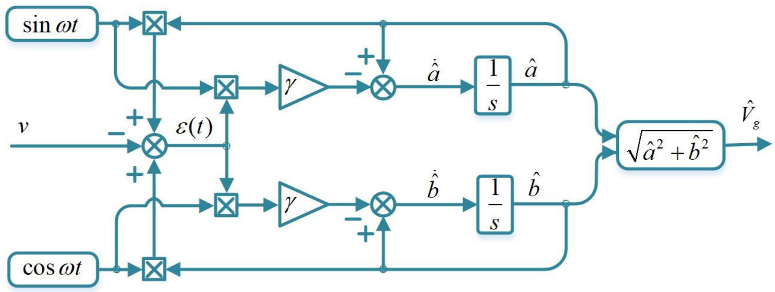

FIGURE 3. Proposed method for the amplitude estimation of the single-phase grid voltage.

TABLE 1. Steady-state performance under different values of γ.

The value of γ	Estimation error (p.u.)
0.04	0.012
0.05	0.017
0.06	0.019
0.07	0.018
0.08	0.021
0.09	0.020
1.0	0.023

TABLE 2. Estimation error under different frequency deviation.

Frequency deviation (Hz)	Estimation error (p.u.)
±0.1	±0.001
±0.3	±0.004
±0.5	±0.007

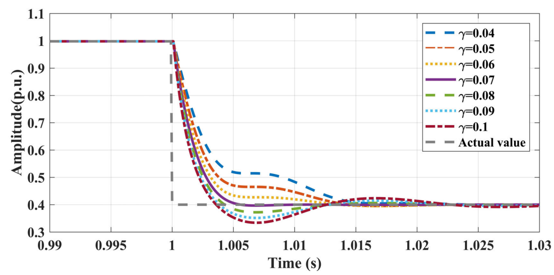

FIGURE 4. Performance comparison of the proposed fast amplitude estimation (FAE) under different values of γ.

the performance of the proposed FAE. To discuss the relationships between the chosen parameter γ and the performance of the proposed method, FAE is tested with different γ under a voltage drop from 1 p.u. to 0.4 p.u. and the results are shown in Fig. 4. It is observed from Fig. 4 that a large γ results in a small fall time. However, too large γ will cause an overshoot and its settling time will slow down, as shown in the case of $\gamma = 0.1$. Meanwhile, the proposed method FAE is also tested with different values of γ under harmonic distortion, which contains the fifth- and seventh-order harmonic disturbances of 0.03 p.u. and 0.01 p.u., respectively. The simulation results are shown in TABLE 1. It can be observed that a large γ results in large estimation error. Above all, $\gamma = 0.07$ is the best choice for both dynamic and steady-state performance of FAE.

In addition, it should be pointed out that the proposed FAE requires the grid frequency information for generating the functions, $\sin\omega kT_s$ and $\cos\omega kT_s$, which can be obtained by a frequency-locked loop. However, to maintain the dynamics of the proposed method, the frequency for $\sin\omega kT_s$ and $\cos\omega kT_s$ in this paper is set as the grid nominal frequency, while the robustness against the frequency jump is still high due to the adaptive scheme in the proposed method, which will be confirmed by the experimental results in the next section.

IV. EXPERIMENT RESULTS

In this section, experimental tests are performed to verify the effectiveness of the proposed FAE. The parameters of the proposed FAE are chosen as $\gamma = 0.07$, and the nominal frequency is 50 Hz. The sampling frequency is *10 kHz*. Meanwhile, the estimation achieved by the SOGI-PLL [12] system is also compared through experimental tests. The parameters of SOGI-PLL are set as $k_p = 92$ and $k_i = 4232$. Similar with the setup in [33] and [34], Fig. 5 shows the hardware implementation of the experimental platform for the proposed method, which is based on a digital signal processor (DSP) TMS320F28335. The voltage sag is generated by an ac power generator, the grid amplitude is calculated by a DSP-based controller, and the detection results are displayed by an oscilloscope.

Case 1: Fig. 6 shows the experimental results under a voltage drop of 0.6 p.u.. It can be observed in Fig. 6 that the proposed FAE method can estimate the amplitude of the grid voltage with zero steady-state error, and its settling time is less than 5 ms. When compared to the estimations by the SOGI-PLL, the proposed method has faster dynamics, as shown in Fig. 6.

TABLE 3. Comparison with different methods.

Detection method	Settling time without harmonics (ms)	Settling time with harmonics (ms)	Estimation error under harmonic distortion
CDSC-PLL [22]	9.5	9.5	1.16%
APF-PLL [16]	6.5	--*	13.3%
Adaptive observer [28]	5.6	--*	11.3%
Proposed method	4	3.9	3.7%

*The steady-state errors of the APF-PLL and the adaptive observer [20] are larger than 5% under harmonic distortion. Hence, they have no settling time shown in Table II according to 5% criterion.

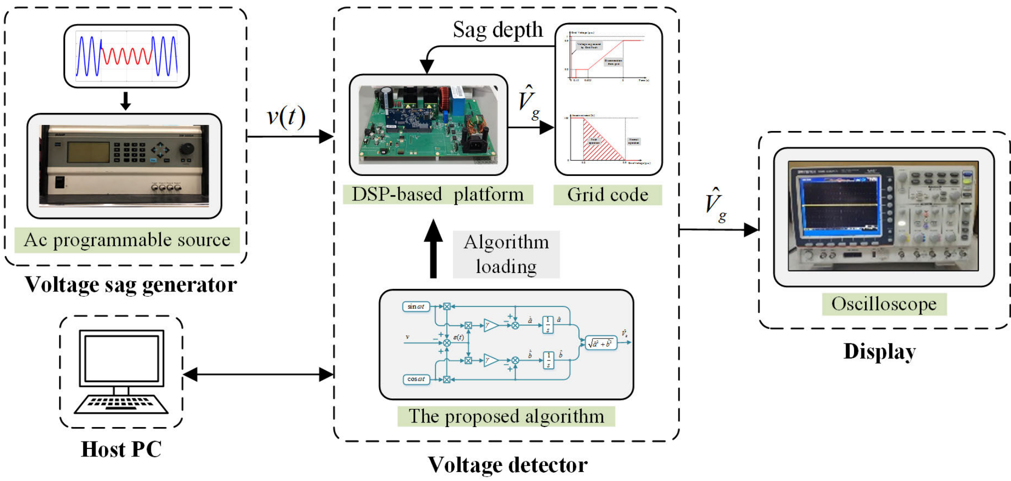

FIGURE 5. Experimental setup.

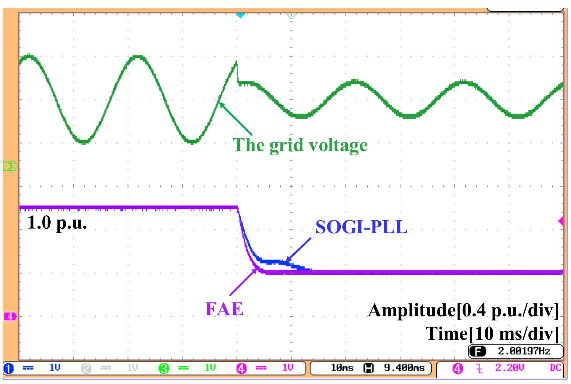

FIGURE 6. Performance comparison of the proposed fast amplitude estimation (FAE) and the estimation by the SOGI-PLL under a voltage drop of 0.6 p.u.

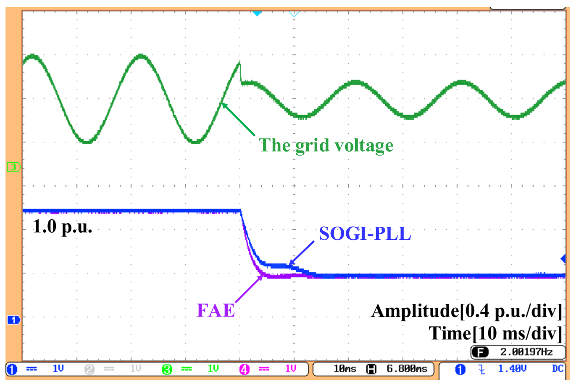

FIGURE 7. Performance comparison of the proposed fast amplitude estimation (FAE) and the estimation by the SOGI-PLL in the case of a voltage sag of 0.6 p.u. and a frequency jump of 1 Hz.

Case 2: Fig. 7 compares the performance of the proposed method and the SOGI-PLL method in the case of a grid disturbance with a voltage sag of 0.6 p.u. and a frequency jump of 1 Hz. As shown in Fig. 7, the proposed FAE method can accurately estimate the amplitude of the grid voltage. Further observations from Fig. 7 indicate that the proposed FAE method has fast dynamics and also high robustness against frequency jumps even the nominal frequency was adopted (as discussed in Section III).

To further verify the robustness against frequency jump, the proposed method is tested under different frequency deviations. According to the grid code [32] on frequency deviation of power systems, the frequency jumps are limited in ±0.5 Hz. Hence, the proposed method is further tested

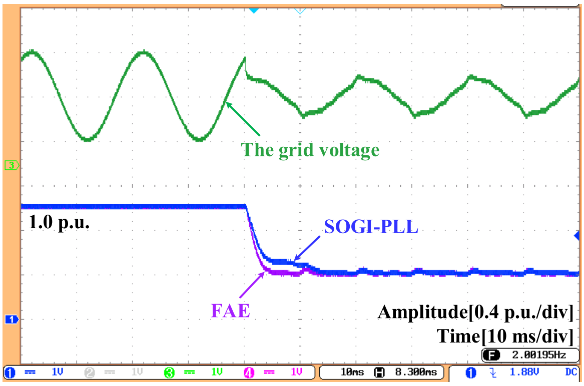

FIGURE 8. Performance comparison of the proposed fast amplitude estimation (FAE) and the estimation by the SOGI-PLL under a voltage drop of 0.6 p.u., where the grid voltage also contains 5% 3rd, 6% 5th, 5% 7th, 1.5% 9th and 3.5% 11th-order harmonics respectively.

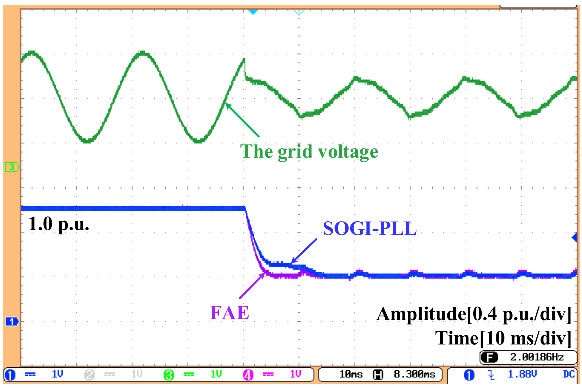

FIGURE 9. Performance comparison of the proposed fast amplitude estimation (FAE) and the estimation by the SOGI-PLL in the case of a voltage sag of 0.6 p.u. where the grid voltage also contains 5% 3rd, 6% 5th, 5% 7th, 1.5% 9th and 3.5% 11th-order harmonics respectively and a frequency jump of 1 Hz.

under different frequency deviations ($\leq$0.5Hz). The results are shown in TABLE 2. The maximum estimation error is $\pm$0.7% p.u.. It shows the proposed method has good robustness against frequency jump.

Case 3: In addition, the two estimation methods are tested under harmonics. Fig. 8 shows the experimental results under a voltage drop of 0.6 p.u. in the grid voltage, which also contains the 5% 3rd, 6% 5th, 5% 7th, 1.5% 9th and 3.5% 11th-order harmonics respectively. In this case, the proposed method again can estimate the amplitude of the distorted grid voltage with fast dynamics. Moreover, the harmonic attenuation capability of the proposed method is the same as that of the SOGI-PLL.

Case 4: In this case, the two methods are conducted under a voltage drop of 0.6 p.u. in the grid voltage, which also contains the 5% 3rd, 6% 5th, 5% 7th, 1.5% 9th and 3.5% 11th-order harmonics as well as 1 Hz frequency jump. The experiment results are shown in Fig. 9. It is obvious that the FAE and the SOGI-PLL methods both have a slight fluctuation in the amplitude estimation. However, the settling time of the SOGI-PLL method is longer than that of the FAE method.

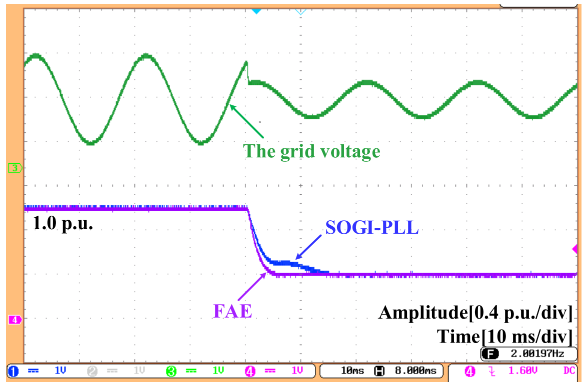

FIGURE 10. Performance comparison of the proposed fast amplitude estimation (FAE) and the estimation by the SOGI-PLL under the noise disturbances and a voltage drop of 0.6 p.u.

Case 5: In order to verify the noise robustness of the proposed method, the experiment results under noise disturbances are shown in Fig. 10. From Fig. 10, it is seen that the steady-state performance of FAE is as good as SOGI-PLL under noise disturbances. Moreover, the FAE shows the fast dynamics again in this case.

In order to further illustrate the performance of the proposed method, a comparison between the proposed FAE and several other methods including CDSC-PLL, APF-PLL and the adaptive observer proposed in [30], under ideal grid and harmonic distortions, respectively. The parameter of CDSC-PLL is set as: $k_p = 92$ and $k_i = 4232$. The parameters of APF-PLL is set as: $k_p = 92$ and $k_i = 4232$. The parameters of the adaptive observer in [30] are set as: $k_p = 444$, $k_i = 4232$, $\tau = 0.05$, $L = [-1.2, -1]$. From TABLE 3, it is obvious that the response time of the PLL-based methods is much longer than the non-PLLs methods because of the existence of the PLL. Moreover, the APF-PLL is unable to track the voltage amplitude accurately under the harmonic variation. Compared to CDSC-PLL, APF-PLL and the adaptive observer proposed in [30], the proposed method has fast detection speed under both ideal and harmonic conditions, and its response time are 4ms and 3.9ms respectively. In addition, the proposed FAE has good robustness against harmonics. In summary, the proposed method shows a satisfactory performance in LVRT operation.

Above all, the experimental results demonstrate the strong performance of the proposed FAE method in terms of fast dynamics. Thus, it can be a promising solution for single-phase systems to enhance the performance under grid faults.

V. CONCLUSION

This paper has proposed a fast amplitude estimation method for single-phase systems to enhance the LVRT operation performance. The estimation is achieved by solving an algebraic model with two unknown parameters, which reflect the amplitude of the grid voltage. Based on the obtained model, a parameter estimator is introduced to identify the two parameters and then the estimation is realized. Compared to the SOGI-PLL method, the proposed solution is a

PLL-independent method, and it has fast dynamics. Experimental tests have verified the performance. The proposed method can be a promising solution for single-phase systems operating under grid faults.

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